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Description

Gas Turbine Engine Cooling System and Method

Cross Reference to Related Applications

[0001] Commonly assigned U.S. Application No. 10/249,967 filed on May 22, 2003 discloses a rotary injector that can be used to inject fuel into a gas turbine engine.

Brief Description of Drawings

[0002] In the accompanying drawings:

[0003] *FIG. 1* illustrates a cross-sectional view of gas turbine engine incorporating a system for cooling the turbine rotor and the associated blades thereof;

[0004] *FIG. 2* illustrates a isometric view of a portion of a bladed rotor and associated fragmentary sectional views thereof;

[0005] *FIG. 3* illustrates a diagram of the relationship between fuel pressure and radial location within the bladed rotor of the gas turbine engine illustrated in *Fig. 1*;

[0006] *FIG. 4* illustrates a diagram of the density and state of fuel

as a function of temperature and pressure;

[0007] *FIG. 5* illustrates a cross-sectional view of a portion of a bladed rotor and an associated thermosiphon process therein; and

[0008] *FIG. 6* illustrates a cross-sectional view of gas turbine engine incorporating another embodiment of a system for cooling the turbine rotor and the associated blades thereof.

DETAILED DESCRIPTION

[0009] Referring to *Fig. 1*, in a *gas turbine engine 10*, *fuel 12* and *air 14* are combusted in a *combustion chamber 16* so as to generate relatively hot, relatively high pressure *exhaust gases 18.1* which are directed through a *turbine 20* comprising a *bladed rotor 22*, e.g. a *rotor 24* incorporating a plurality of *blades 26* on the periphery thereof. The *turbine 20* is operatively coupled to a *shaft assembly 28*, e.g. with a *bolt 30* through an associated *flange 32*, and the *shaft assembly 28* is supported from the *housing 34* of the *gas turbine engine 10* by one or more *bearings 35* that provide for rotation of the *shaft assembly 28* and *turbine 20* relative thereto. The action of the *exhaust gases 18.1* against the *blades 26* rotates the *turbine 20* and the *shaft assembly 28*, which, for example, is operatively coupled to a compressor (not illustrated) that

provides for pumping the *air 14* into the *combustion chamber 16*. The *exhaust gases 18.2* discharged from the *turbine 20* are at a relatively lower pressure than the *exhaust gases 18.1* upstream thereof as a result of the work done by the *exhaust gases 18.1* on the *turbine 20*.

[0010] Under some conditions, for example, when operated as a turbo-jet engine to propel a high-speed aircraft at high Mach numbers, the *air 14* supplied to the *gas turbine engine 10* is relatively hot, which contributes to increased temperature of the *exhaust gases 18.1*, and which is not sufficiently cool to otherwise provide for adequately cooling the *turbine 20*, so that the temperature of the associated *blades 26* can become excessive. Under these conditions, the*fuel 12* is generally sufficiently cool to provide sufficient cooling capacity to cool the *gas turbine engine 10*, and particularly, to cool the *turbine 20* thereof, which might otherwise be susceptible to thermally induced failure, whereby the *gas turbine engine 10* is cooled by directing *fuel 12* from a *source of fuel 36* through the *rotor 24* and *blades 26* of the *turbine 20* to cool the *rotor 24* and the *blades 26* of the *turbine 20*, and then combusting this *fuel 12* -- heated by the cooling process -- in the *combustion chamber 16*.

[0011] For example, *fuel 12* from a *source of fuel 36* comprising a

fuel tank and an associated fuel pump is supplied through a *first control valve 37* to an *orifice 38* that is relatively fixed with respect to the *housing 34* of the *gas turbine engine 10*. The *fuel 12* is discharged from the*orifice 38* into an *inlet 40* of a *first rotary fluid trap 42* operatively coupled to the*rotor 24* so as to rotate therewith. The *outlet 44* of the *first rotary fluid trap 42* is in fluid communication with a *first portion 46.1* of a *first cavity 46* that is bounded by a portion of a *first side 48* of the *rotor 24* and by a first bounding surface of an *aft cover 50* of which the *first rotary fluid trap 42* is a part.

[0012] The *first rotary fluid trap 42* comprises a *passage 52* that provides for fluid communication between the *inlet 40* and the *outlet 44*, wherein, in accordance with the teachings of *U.S. Patent Nos.4,870,825 and 6,269,647*, and of *U.S. Application No. 10/249,967*, each of which is incorporated herein by reference, the *passage 52* is adapted so the when the *first rotary fluid trap 42* is rotated, a centrifugal acceleration at any point within the *passage 52* is greater than a centrifugal acceleration at any point on either the *inlet 40* or the *outlet 44*. Accordingly, when the rotating *passage 52* is filled with a relatively high density medium, such as *liquid fuel 12.1*, the radial levels of the *inlet 40* and *outlet 44* will be equal when there is no pressure differential therebetween, and will be

otherwise unequal by an amount dependent upon the magnitude of the pressure differential and the speed of rotation. For a relatively low pressure supply of *liquid fuel 12.1* to an *inlet 40* of a *passage 52* feeding a relatively high pressure region at the *outlet 44*, the *passage 52* can prevent backflow therethrough. Accordingly, the *first rotary fluid trap 42* provides for isolating the pressure in the *first cavity 46* -- which can be relatively high -- from the pressure at the *inlet 40* of the *passage 52* -- which is relatively lower -- thereby providing for supplying *fuel 12* to the *inlet 40* of the *first rotary fluid trap 42* across a *rotary junction 54* between the rotating *inlet 40* and the relatively fixed *orifice 38*, whereby *liquid fuel 12.1* sprayed from the relatively fixed *orifice 38* becomes captured by an *internal trough 56* associ-ated with the *inlet 40* of the *first rotary fluid trap 42* as a re-sult of centrifugal acceleration acting upon the *liquid fuel 12.1* upon striking the*internal trough 56* and rotating there-with.

[0013] The *aft cover 50* comprises an *intermediate rim 58* and an *outer rim 60* that engage respective *first 62.1* and *second 62.2 lips* formed on the *first side 48* of the*rotor 24*. The *outer rim 60* is sealed to the *second lip 62.2* so as to prevent leakage of *fuel 12* from the joint therebetween. The *intermediate rim*

58 incorporates at least one *passage 64* that provides for fluid communication between *first 46.1* and *second 46.2 portions* of the *first cavity 46*. The *second portion 46.2* of the *first cavity 46* is in fluid communication with a plurality of *first passages 66* that extend through the *rotor 24*. Referring also to *Fig. 2*, each *first passage 66* has a *first opening 68* on the *first side 48* of the *rotor 24*, and a *second opening 70* on a *second side 72* of the *rotor 24*, the *first 48* and *second 72 sides* being opposite to one another.

[0014] The *first passages 66* are in fluid communication with a *second portion 74.2* of a *second cavity 74* that is bounded by a portion of the *second side 72* of the *rotor 24* and by a second bounding surface of a *forward cover 50*, wherein the *forward cover 50* comprises an *intermediate rim 78* and an *outer rim 80* that engage respective *first 82.1* and *second 82.2 lips* formed on the *second side 72* of the*rotor 24*. The *outer rim 80* is sealed to the *second lip 82.2* so as to prevent leakage of *fuel 12* from the joint therebetween. The *intermediate rim 78* incorporates at least one *passage 84* that provides for fluid communication between the *second portion 74.2* of the *second cavity 74* and a*first portion 74.1* thereof. The *first portion 74.1* of the *second cavity 74* is in fluid communication with the *interior 86* of a *shaft 88* of the *shaft assembly 28* via at

least one *passage 90* through the *shaft 88*, and the *interior 86* of the *shaft 88* is in fluid communication with a *first discharge orifice 92* through at least one other *passage 94* through the *shaft 88*. The *first discharge orifice 92* is in fluid communication with the *combustion chamber 16*, and thereby provides for a discharge of *fuel 12* directly from the rotating *shaft 88* to the *combustion chamber 16*. The *first discharge orifice 92* is, for example, a part of a *second rotary fluid trap 96* that provides for isolating the relatively high pressure of the *combustion chamber 16* from the relatively lower pressure of the interior of the *shaft 88* and the *first portion 74.1* of the *second cavity 74*, whereby the principles of structure and operation of the *second rotary fluid trap 96* are the same as those of the *first rotary fluid trap 42* described hereinabove.

[0015] Referring to *Figs. 2* and*5*, the *first passages 66* and associated *first 68* and *second 70 openings* are substantially uniform in size and shape, and uniformly distributed so as to provide a mechanically balanced *rotor 24*. The *axial shape 98* of the *first passages 66* is adapted to at least partially conform to a profile of the associated *blades 26*. For example, in the embodiment illustrated in *Fig. 2*, the first *passages 66* have *chevron axial shape 98.1* so as to at least partially conform to

the camber of the *blades 26*. A *first set 66.1* of *first passages 66* extend through the *rotor 24* at associated circumferential locations that are substantially between the associated circumferential locations of the associated *blades 26*, and a *second set 66.2* of *first passages 66* extend through the *rotor 24* at associated circumferential locations that are substantially aligned with the associated circumferential locations of the associated *blades 26*, whereby the *first 66.1* and *second 66.2* sets of *first passages 66* are interleaved with respect to one another. Each of the *blades 26* incorporates a plurality of *second passages 100* that extend substantially radially therewithin, each of which at a *first end 102* thereof intersects an associated *first passage 66* of the *second set 66.2* that is aligned therewith. For example, the *second passages 100* are substantially linear along the length thereof. As illustrated in *Fig. 2*, the diameter of the *second passages 100* within a particular *blade 26* can be adapted in accordance with the associated blade thickness proximate thereto, so as to provide sufficient heat transfer between the *outer surface 104* of the *blade 26* and the *surface 106* of the associated *second passage 100* while providing for adequate blade strength. The distal *second ends 108* of the *second passages 100* are terminated in a *third cavity 110* proximate to a *tip*

112 of the *blade 26*, wherein the *third cavity 110* provides for fluid communication amongst the *second passages 100* within the associated *blade 26*. For example, the *third cavity 110* is formed by a *end cap 114* that is separated from the *second ends 108* of the *second passages 100*, and which is secured at its periphery to the *edge 116* of the *blade 26*. The *blades 26* are closed with respect to the *combustion chamber 16* relative to the *fuel 12* within the *blades 26*, so that all of the *fuel 12* enters the *combustion chamber 12* at a location that is radially inward of the *blades 26*.

[0016] Accordingly, the *gas turbine engine 10* comprises a *rotatable portion 118* that is rotatable with respect to a *housing 34* of the *gas turbine engine 10*, wherein the *rotatable portion 118* comprises the *turbine 20* / *bladed rotor 22*, comprising the *rotor 24* and the *blades 26*; the *aft cover 50* and associated *first rotary fluid trap 42*; the *forward cover 50*; and the *shaft assembly 28* / *shaft 88* and associated *first discharge orifice 92* / *second rotary fluid trap 96*, all of which rotate in unison with a rotating frame of reference. After discharge from the *relatively fixed orifice 38*, the *fuel 12* is contained within the *rotatable portion 118* until discharge directly into the *combustion chamber 16* from the *first discharge orifice 92* of the *rotatable portion 118* in the rotating frame of reference Accord-

ingly, because all of the elements of the *rotatable portion 118* rotate in unison with the rotating frame of reference, these elements can be readily sealed to one another as necessary to contain the *fuel 12* therein, for example, at the junctions of the *outer rims 60,80* of the *first 50* and *second 76 bounding surfaces* with the *second lips 62.2, 82.2* of the *rotor 24*, which could otherwise be problematic if it were necessary to provide for sealing across a relatively moving junction of elements to be sealed to one another.

[0017] With the *gas turbine engine 10* in operation, *liquid fuel 12.1* provided by the *source of fuel 36* and regulated by the *first control valve 37* is discharged from the *relatively fixed orifice 38* into the *internal trough 56* of the *inlet 40* of the *first rotary fluid trap 42*. The discharged *liquid fuel 12.1* is captured by the *internal trough 56* as a result of the centrifugal acceleration acting upon the discharged *liquid fuel 12.1* which commences rotation with the *rotatable portion 118* upon impact with the *internal trough 56* or the *liquid fuel 12.1* contained therein. *Liquid fuel 12.1* entering the *inlet 40* of the *first rotary fluid trap 42* is pumped through the associated *passage 52* of the *first rotary fluid trap 42* by the action of centrifugal acceleration forces acting upon the *liquid fuel 12.1* contained within the *first rotary fluid trap 42*, and this action of cen-

trifugal acceleration forces also isolates the relatively low pressure at the *inlet 40* of the *first rotary fluid trap 42* from a relatively high pressure at the *outlet 44* thereof. Upon exiting the *outlet 44* of the *first rotary fluid trap 42*, the *fuel 12* is accelerated radially outwards, whereby *liquid fuel 12.1* -- which is relatively dense in comparison with associated fuel vapor -- tends to follow the inside of the *aft cover 50*.

[0018] During normal operation of the *gas turbine engine 10*, the hottest portion of the *turbine 20 / bladed rotor 22* are the *blades 26* which are directly exposed to the relatively hot *exhaust gases 18.1* from the *combustion chamber 16*. Heat from the *blades 26* is transferred to the *rotor 24* and *associated first 50* and *second 76 bounding surfaces*, which provides for heating any *fuel 12* in the associated *first 46* and *second 74* cavities that are adjacent to the *first 48* and *second 72 sides* of the *rotor 24*. Accordingly, the temperature of the *rotor 24* and adjacent *aft cover 50* increases with decreasing distance from the *blades 26*, so that *fuel 12* within the *first cavity 46* is heated as it flows radially outwards. Furthermore, referring to *Fig. 3*, the centrifugal acceleration acting upon the *fuel 12* increases with increasing radial distance within the *first cavity 46*, which increases the associated pressure thereof. *Fuel 12* in the *first 46* or *second 74 cavities* is rotated

by viscous forces generated as a result of relative motion of the *rotor 24* and *aft cover 50* acting with respect to the liquid or vapors in the associated *first 46* or *second 74 cavities*, whereas *fuel 12* in the *first 66* or *second 100 passages* is forced to rotate with the *rotor 24* and *blades 26*. Accordingly, as illustrated in *Fig. 3*, in the former region of viscous rotation, the fuel pressure increases at a lower rate with respect to radial distance than in the latter forced region because of slippage within the flow stream than can occur in the former region but not in the latter. Referring to *Fig. 4*, as the *fuel 12* is heated in the *first portion 46.1* of the *first cavity 46*, the *fuel 12* is transformed from a saturated liquid to a saturated vapor, as indicated by the locus of points labeled *"A"*, which is also shown in *Fig. 1*. As the *fuel 12* flows from the *first 46.1* to the *second portion 46.1* of the *first cavity 46*, the *fuel 12* becomes superheated, and may exhibit a mixture of states as indicated by the points labeled *"B"* and *"C"* in *Figs. 1* and*4*.

[0019] As the *fuel 12* flows through the *first opening 68* into the *first passage 66*, it becomes further heated and pressurized. *Fuel 12* in the *first set 66.1* of*first passages 66* flows therethrough, out of the *second openings 70* thereof, and then into the *second portion 74.2* of the *second cavity 74*, and in the process,

provides for cooling the *rim 120* of the *rotor 24* in the regions between the *blades 26*. Referring to *Fig. 5*, the centrifugal acceleration field causes relatively dense *fuel 12* in the *second set 66.2* of*first passages 66* to flow into the *second passages 100* intersecting therewith, which displaces *fuel 12* therein that has become relatively more heated and less dense, responsive to a thermosiphon process that is driven by the centrifugal acceleration field and by the decrease in density as *fuel 12* becomes heated as a result of heat transfer from the *blades 26* which cools the *blades 26*. The *thermosiphon flow 122* within the *second passages 100* and between the *first 66* and *second 100 passages* causes a continuous exchange of relatively *cooler fuel 12.2* for relatively *hotter fuel 12.3*, which is also illustrated by the points *"D"*, *"E"* and *"F"* in *Figs. 4* and *5*. The relatively *hotter fuel 12.3* ultimately flows through the *second opening 70* of the *second set 66.2* of*first passages 66* and into the *second portion 74.2* of the second cavity. The *second set 66.2* of*first passages 66* provides for the flow of *fuel 12* either directly therethrough from the *first opening 68* to the *second opening 70* along a *first flow path 124*, which provides for cooling the *rotor 24* at the base of the associated *blade 26*; or indirectly after first flowing along a *second flow path 126* which includes one or more

second passages 100 responsive to a thermosiphon process, which provides for cooling the associated *blade 26* of the *turbine 20*.

[0020] The relatively less dense *heated fuel 12.3* in the *second portion 74.1* of the *second cavity 74* flows through the *passage 84* into the *first portion 74.1* of the *second cavity 74* after being displaced by relatively more dense less heated *fuel 12* from the *first passages 66*. As the fuel flows radially inwards in the *second cavity 74*, the pressure thereof is reduced, and the *fuel 12* is cooled by exchange of heat with the relatively cooler surroundings, transforming from a superheated vapor to a saturated vapor then a saturated liquid, as indicated by the locus of points labeled *"G"* on *Fig. 4* corresponding to the location similarly labeled in *Fig. 1*. The *fuel 12* then flows through the *passage 90* through the *shaft 88*, through the *interior 86* of the *shaft 88*, out of a second passage through the *shaft 88* and into the *combustion chamber 16* through the *first discharge orifice 92* which is part of a *second rotary fluid trap 96*.

[0021] The above-described system and method of cooling the *turbine 20* -- wherein *fuel 12* is delivered by a *first fuel distribution circuit 128* from the *source of fuel 36* through the *first control valve 37* to the *rotor 24* and *blades 26* -- is beneficially

used when the *turbine 20* is at a temperature that is sufficient to vaporize the *fuel 12* so as to mitigate against interfering with the mechanical balance of the *turbine 20*. In accordance with another aspect, it is beneficial to utilize a *second fuel distribution circuit 130* that provides for injecting fuel directly into the *combustion chamber 16* without involving flow through the *rotor 24* and *blades 26*. Referring to *Fig. 1*, *liquid fuel 12.1* supplied from the *source of fuel 36* is regulated by a *second control valve 132* and delivered to a *second discharge orifice 134*, for example, a part of a *third rotary fluid trap 136*, for example, operatively coupled to the *shaft 88*, wherein *fuel 12* is supplied from the *second control valve 132* through a separate *passage 138* in the interior of the *shaft 88*. For example, the *first 37* and *second 130 control valves* would be controlled so that all of the *fuel 12* to the *gas turbine engine 10* is delivered by the *second fuel distribution circuit 130* during startup and warm-up conditions. After the *gas turbine engine 10* has warmed up, in one embodiment, the *second fuel distribution circuit 130* provides for a sufficient amount of *fuel 12* to maintain an idle operating condition, and the remaining *fuel 12* is provided by the *first control valve 38* via the *first fuel distribution circuit 128* responsive to operationally dependent demand. In another embodiment,

all of the *fuel 12* might be delivered by the *first fuel distribution circuit 128* after the *gas turbine engine 10* has warmed up. In yet another embodiment, some other relative distribution of *fuel 12* between the *first 128* and *second 130 fuel distribution circuits* is used.

[0022] Referring to *Fig. 6*, in accordance with another embodiment, the *first discharge orifice 92* and associated *second rotary fluid trap 96* are incorporated in the *forward cover 76*, so as to provide for injection of *fuel 12* directly into the *combustion chamber 16* therefrom, without involving the*shaft 88* as an associated flow path.

[0023] In addition to providing for cooling the *blades 26* and*rotor 24* of the *turbine 20*, the *first fuel distribution circuit 128* also provides for a regenerative recovery of heat from the *exhaust 18.1* so as to provide for improved operating efficiency, particularly for stationary applications.

[0024] While specific embodiments have been described in detail in the foregoing detailed description and illustrated in the accompanying drawings, those with ordinary skill in the art will appreciate that various modifications and alternatives to those details could be developed in light of the overall teachings of the disclosure. Accordingly, the particular arrangements disclosed are meant to be illustrative

only and not limiting as to the scope of the invention, which is to be given the full breadth of the appended claims and any and all equivalents thereof.

[0025] We Claim: